Towards a resolution of the discrepancy between different estimators of star formation rate

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ABSTRACT

Different wavelength regimes and methods for estimating the space density of the star-formation rate (SFR) result in discrepant values. While it is recognised that ultra-violet (UV) and Hα emission line data must be corrected for the effects of extinction, the magnitude of the required correction is uncertain. Even when these corrections are made there remains a significant discrepancy between SFRs derived from UV and Hα measurements compared with those derived from far-infrared (FIR) and radio luminosities. Since the FIR/radio derived SFRs are not affected by extinction, and simple corrections to reconcile the UV and Hα measurement with these do not fully account for the discrepancies, a more sophisticated correction may be required. Recent results suggest that at least part of the solution may be a form of extinction which increases with increasing SFR (or luminosity, given the common assumption that SFR is proportional to luminosity). We present an analysis of the effects of a dust reddening *dependent on star formation rate* applied to estimators of SFR. We show (1) that the discrepancies between Hα and FIR/radio SFR estimates may be explained by such an effect, and we present an iterative method for applying the correction; and (2) UV-based estimates of SFR are harder to reconcile with FIR/radio estimates using this method, although the extent of the remaining discrepancy is less than for a non-SFR-dependent correction. Particularly at high redshift, our understanding of extinction at UV wavelengths may require a still more complex explanation.

Subject headings: dust, extinction — galaxies: evolution — galaxies: starburst

1. Introduction

In recent years a variety of observations and observational methods have been used to contribute to our understanding of the global star formation history of the universe. It is generally agreed that ρ^*, the comoving space density of the star formation rate (SFR) in galaxies, rises by an order of magnitude between $z = 0$ and $z = 1$ (Lilly et al. 1996; Connolly et al. 1997; Hogg et al. 1998; Flores et al. 1999; Haarsma et al. 2000). Despite several observations encompassing $1 < z < 2$ and

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$z > 2$ however, (Madau et al. 1996; Connolly et al. 1997; Hughes et al. 1998; Yan et al. 1999; Steidel et al. 1999; Hopkins et al. 2000) it is still unclear whether the evolution of ρ^* reaches a peak around $z \approx 1.5$ and decreases significantly thereafter (e.g., Madau et al. 1996), or whether it stays flat to much higher redshifts (e.g., Steidel et al. 1999; Haarsma et al. 2000).

Some of this uncertainty may be related to the difficulty of making corrections for extinction at ultra-violet (UV), optical and near-infrared wavelengths. In the absence of extinction corrections there is a clear discrepancy between values of ρ^* estimated from observations at radio or far-infrared (FIR) wavelengths and those estimated from Hα and UV measurements. Even when simple extinction corrections to the UV and Hα measurements are made, however, systematic differences persist between estimates of SFR or ρ^* made at differing wavelengths, This can be seen, for example, in the distribution of SFRs for (1) individual objects in a study of local galaxies by Cram et al. (1998, their Figure 1), and in a multiwavelength study of Selected Area 57 (SA57) by Sullivan et al. (2001, their Figure 3); and (2) globally, in a diagram showing the redshift dependence of ρ^* by Haarsma et al. (2000, their Figure 10).

Several efforts have been made to address this concern. A detailed investigation of some of these issues is presented in Adelberger & Steidel (2000), with particular emphasis on obscuration at UV wavelengths. Calzetti & Heckman (1999) have modelled the evolution with redshift of galaxy opacity for applying corrections to UV-derived estimates of ρ^*. Meurer et al. (1999) have refined a technique for correcting UV luminosities for attenuation using rest-frame luminosities alone. This method is based on an observed correlation between the FIR/UV flux ratio and β the UV spectral slope. Gordon et al. (2000) presents a more general flux ratio method for establishing wavelength-specific attenuations for individual galaxies, based on assumed SEDs.

We extend these investigations by first deriving an SFR-dependent (or luminosity-dependent) attenuation from existing observations. We then examine its efficacy by applying it to Hα and UV estimates of SFR for a large sample of local galaxies. The examination is subsequently expanded to investigate the effects of the application to global SFR densities, derived from Hα or UV measurements, spanning a broad redshift range,

In Section 2 we comment on the use of FIR and 1.4 GHz luminosities as estimators of SFR. Section 3 describes the formulation of an SFR-dependent reddening parametrisation. This is then applied to correct estimates of SFR for a sample of local galaxies in Section 4, and subsequently to estimates of ρ^* spanning a broad redshift range in Section 5. Section 6 presents a brief investigation of the empirical relation between $\mathrm{SFR}_{\mathrm{UV}}$ and intrinsic SFR, and its effects when used blindly to correct estimates of ρ^*_{UV} at all redshifts.

Throughout this paper we have used SFR calibrations defined consistently to account for the mass range $0.1 < M < 100\,M_\odot$ assuming a Salpeter IMF. We adopt the Hα and UV SFR calibrations given by Kennicutt (1998), shown in Table 1. Our assumed FIR and 1.4 GHz SFR calibrations are also given in this Table, and are explained in more detail below. We assume $H_0 = 75\,\mathrm{km\,s^{-1}Mpc^{-1}}$ and $q_0 = 0.5$, and have converted previously published estimates of SFR to our assumed calibrations and this cosmology, where necessary, to ensure consistency.

2. FIR and Radio estimates of SFR

The intrinsic SFR of a galaxy cannot be estimated directly from observations at UV or optical wavelengths because of the uncertainties caused by the presence of unknown amounts of obscuring dust. Indicators of SFR at longer wavelengths, at which dust is transparent, are sought as an alternative. In the past few decades FIR luminosity has been used extensively as an estimator of current star formation rate in galaxies, and throughout this paper we have adopted the calibration given by Kennicutt (1998), which is shown in Table 1. While FIR luminosity is expected to be an excellent SFR tracer for strong, compact, dusty starbursts, the situation is less clear when the disks of normal galaxies are being examined. The uncertainties in using FIR luminosity as an SFR estimator for normal galaxies are described by Kennicutt (1998), and while FIR luminosity in late-type star-forming galaxies appears to correlate well with other estimators of SFR, this is not generally the case for early-type spirals and ellipticals.

Table 1

Assumed luminosity-to-SFR calibrations.

Indicator	Calibration
UV	$\mathrm{SFR_{UV}} = L_{\mathrm{UV}}/7.14 \times 10^{20}\,\mathrm{W\,Hz^{-1}}$
Hα	$\mathrm{SFR_{H\alpha}} = L_{\mathrm{H\alpha}}/1.27 \times 10^{34}\,\mathrm{W}$
FIR	$\mathrm{SFR_{FIR}} = L_{\mathrm{FIR}}/5.81 \times 10^{9}\,L_{\odot}$
1.4 GHz	$\mathrm{SFR_{1.4GHz}} = L_{\mathrm{1.4GHz}}/8.4 \times 10^{20}\mathrm{W\,Hz^{-1}}$

At still longer wavelengths, populations of star-forming galaxies have been detected in increasingly sensitive radio surveys (e.g. Windhorst et al. 1984, 1985; Oort 1987; Hopkins et al. 1999). As well as supporting the well-established radio-FIR correlation for disk or star-forming galaxies (which extends over more than 4 orders of magnitude and is commonly accepted to be a product of star formation processes, see review by Condon 1992), estimates of SFR from measurements of 1.4 GHz radio luminosity are now becoming more common (e.g. Condon 1992; Cram et al. 1998; Haarsma et al. 2000). We have adopted the 1.4 GHz SFR calibration as given by Haarsma et al. (2000), $\mathrm{SFR_{1.4GHz}} = Q(L_{1.4}/4.6 \times 10^{21}\mathrm{W\,Hz^{-1}})$, with $Q = 5.5$ the factor accounting for the inclusion of stars less massive than $5\,M_{\odot}$ (see Table 1).

As a result, the use of radio or FIR luminosities as estimators of SFR appear to be justified for samples of galaxies which lie on the radio-FIR correlation. Admittedly, there are still concerns over the details of the physical processes which produce this correlation (Condon 1992). While the currently favoured explanation are processes related to star formation, some radio-quiet quasars also appear to follow the correlation (Cram et al. 1992), as do Seyfert galaxies lacking compact radio cores (Roy et al. 1998, although with greater scatter in this case). The scatter in the radio-FIR correlation for disk galaxies, while smaller, is also significant and its origins remain unknown. Despite these concerns, long-wavelength estimators of SFR provide a valuable tool which avoids the effects of obscuration, thus allowing useful insights into the properties of star formation in various galaxy populations.

3. An SFR-dependent reddening

Star forming galaxies in the local universe have been shown to exhibit a correlation between obscuration and FIR luminosity, as seen for example in Wang & Heckman (1996). This implies that the obscuration in a galaxy is related to its SFR. This same general effect can also be seen in other recent results, e.g., Adelberger & Steidel (2000), particularly their Figure 11, Calzetti et al. (1995), and Sullivan et al. (2001).

Wang & Heckman (1996) demonstrate a trend between FIR luminosity (L_{FIR}) and the inverse of the Balmer decrement for a small population of normal Hubble types as well as some Markarian starbursts. A similarly small sample of nuclear starburst and blue compact galaxies analysed by Calzetti et al. (1995) show a clear trend between colour excess, (or UV spectral index), and L_{FIR}. Both trends are in the sense of increasing obscuration with increasing L_{FIR}. The scatter in these trends is notable, however, and may be related to intrinsic differences within galaxy populations, as well as between the different populations analysed.

Now, since FIR luminosity for these objects can be treated as an estimator of a galaxy's *intrinsic* star formation rate, this suggests that these relations can be recast in terms of obscuration (colour excess, for example) and $\mathrm{SFR_{FIR}}$. Using the data of Wang & Heckman (1996) we perform a least squares fit to the Balmer decrement (not its inverse) and $\log(L_{\mathrm{FIR}})$ to derive

$$\frac{F_{H\alpha}}{F_{H\beta}} = 0.797 \log\left(\frac{L_{\mathrm{FIR}}}{L_{\odot}}\right) - 3.952. \qquad (1)$$

The Pearson correlation coefficient for this fit is 0.6. Sullivan et al. (2001) independently find a

relation consistent with this result, from observed Balmer decrements for their UV (200 nm) selected-sample. $E(B-V)$, the colour excess appropriate for nebular emission lines, is then calculated using the Balmer decrement (Calzetti et al. 1996)[3]:

$$E(B-V)_{\rm gas} = \frac{\log(R_{\rm obs}/R_{\rm int})}{0.4[k(\lambda_{H\beta}) - k(\lambda_{H\alpha})]}. \quad (2)$$

Here $R_{\rm obs}$ and $R_{\rm int}$(=2.88 for Case B recombination) are the observed and intrinsic values for the Balmer decrement. We can combine Equations 1 and 2 to form a direct relationship between colour excess and FIR luminosity. Figure 1 shows the resulting relation, along with the data used to derive Equation 1, (modified from Figure 10 of Wang & Heckman 1996), and data taken from the independent sample of starburst and blue compact galaxies by Calzetti et al. (1995). Since a negative colour excess is unphysical, we assume that luminosities which give rise to $E(B-V) < 0$ from this relation correspond to zero attenuation, and this is seen in the flattening of the line in Figure 1. Below $L_{\rm FIR} \approx 4 \times 10^{10}\, L_\odot$ the data from Calzetti et al. (1995) appear to be consistent with the trend seen in the Wang & Heckman (1996) data, but at higher luminosities even greater colour excesses are seen. This suggests that for high-SFR galaxies in the local universe, the following analysis may be somewhat conservative.

The relation between colour excess and FIR luminosity can now be transformed to one between colour excess and SFR, using our adopted calibration for $\rm SFR_{FIR}$, and we then find the colour excess appropriate to a given *intrinsic* SFR:

$$E(B-V)_{\rm gas} = 1.965 \log\left[\frac{0.797\log({\rm SFR_{FIR}}) + 3.834}{2.88}\right]. \quad (3)$$

This, then, forms the crux of an SFR-dependent reddening relation. Given the intrinsic SFR for a galaxy (which may be derived from radio as well as FIR luminosities, for example), and a reddening curve, the attenuation to be applied at all wavelengths can be calculated. Using the standard formulation (e.g. Calzetti et al. 2000; Calzetti 1997) the intrinsic luminosity, $L_i(\lambda)$, is related to the observed value, $L_o(\lambda)$, by:

$$L_i(\lambda) = L_o(\lambda) 10^{0.4E(B-V)k(\lambda)}, \quad (4)$$

and since all the assumed SFR calibrations are directly proportional to luminosity, this can be considered to be a relation between intrinsic and observed SFR.

Additionally, and most importantly, since Equation 3 is monotonic even a measurement of the *attenuated* SFR can be used to estimate the amount of reddening. This is done by substituting Equation 3 into Equation 4 (cast in terms of SFR rather than luminosity, since the SFR calibration constant cancels) and solving numerically the resulting transcendental equation, which for the wavelength of Hα can be written:

$$\log(SFR_i) = \log(SFR_{o({\rm H}\alpha)}) + 2.614 \times \log\left[\frac{0.797\log({\rm SFR_i}) + 3.834}{2.88}\right]. \quad (5)$$

Hence, by assuming such a form for an SFR-dependent obscuration, even observations of a single Hα emission line (or other star-formation-sensitive line, such as [OII]) may be used to estimate attenuation and intrinsic SFR.

Now the colour excess appropriate for the stellar continuum, $E(B-V)_{\rm star}$, is related to that for nebular gas emission lines by

$$E(B-V)_{\rm star} = 0.44 E(B-V)_{\rm gas}, \quad (6)$$

(e.g. Calzetti et al. 2000; Calzetti 1997). As a result it should in principle be possible to apply the same procedure to derive appropriate corrections for UV-continuum estimates of SFR. Combining Equations 6, 3 and 4 gives the following relation for UV wavelengths:

$$\log(SFR_i) = \log(SFR_{o({\rm UV})}) + X(\lambda_{\rm UV}) \times \log\left[\frac{0.797\log({\rm SFR_i}) + 3.834}{2.88}\right], \quad (7)$$

[3]We use the reddening curve $k(\lambda) = A(\lambda)/E(B-V)$ for star-forming systems formulated by Calzetti et al. (2000):

$$\begin{aligned} k(\lambda) &= 2.659(-1.857 + 1.040/\lambda) + 4.05 \\ &\qquad (0.63\,\mu m \le \lambda \le 2.20\,\mu m) \\ &= 2.659(-2.156 + 1.509/\lambda - 0.198/\lambda^2 \\ &\quad +0.011/\lambda^3) + 4.05 \\ &\qquad (0.12\,\mu m \le \lambda \le 0.63\,\mu m) \end{aligned}$$

where $X(365\,\mathrm{nm}) = 2.061$, $X(280\,\mathrm{nm}) = 2.512$ and $X(150\,\mathrm{nm}) = 3.574$. Recent results from Adelberger & Steidel (2000) suggest, however, that observed (attenuated) UV luminosity at short wavelengths ($\lambda \approx 160\,\mathrm{nm}$) is a very poor indicator of SFR. They find that while galaxies with high SFRs (and intrinsic UV luminosities) show increased levels of obscuration (see Figure 11 of Adelberger & Steidel 2000) consistent with our primary assumption, the obscuration is such as to attenuate the observed UV luminosities to a remarkably constant level for a broad range of extinctions (see Figure 17 of Adelberger & Steidel 2000). This results in a situation where Equation 7 effectively becomes degenerate, and a knowledge of only the observed UV luminosity is insufficient to regain information about the extent of the obscuration and the corresponding intrinsic luminosity or SFR. In contrast with this result, Figure 3 from Sullivan et al. (2001), comparing $\mathrm{SFR_{UV}}$ derived from observations at $\lambda \approx 200\,\mathrm{nm}$ to $\mathrm{SFR_{1.4GHz}}$, does not show the expected degeneracy, suggesting that perhaps the effect is stronger at shorter wavelengths. As we later show, we also find no such degeneracy in U-band derived SFRs, supporting this suggestion. The above method is thus explored below with regard to UV luminosities using the relations already derived, but placing emphasis on wavelengths longer than 160 nm which appear less likely to show this degenerate effect.

4. Corrections to local SFR estimates

The relationship between (obscured) Hα- and UV-based measures of SFR and measurements of intrinsic SFR (for which we use $\mathrm{SFR_{FIR}}$ or $\mathrm{SFR_{1.4GHz}}$) are given by Equations 5 and 7. These relations are compared with observational measurements for a sample of local galaxies in Figures 2 and 3, using data selected from the compilation of Cram et al. (1998). Figure 3 emphasises the validity of the radio-FIR correlation for this sample, and justifies the strong emphasis on 1.4 GHz based estimates of SFR (and subsequently ρ^*) in our analysis. The "knee" of the curves shown in Figures 2 and 3 marks the SFR at which the derived colour excess from Equation 3 goes to zero from higher values at higher SFRs. For SFRs lower than this value we assume there is no attenuation of the observed luminosity (and hence SFR).

The SFR-dependent reddening formulation seems to account well for the observed discrepancy between $\mathrm{SFR_{H\alpha}}$ and $\mathrm{SFR_{FIR}}$ or $\mathrm{SFR_{1.4GHz}}$ (Figures 2a and 3a). It is also clear that, while this prescription may be useful for examining the trends over large samples, the extent of the intrinsic scatter in the relevant correlations seen in the observations, is quite large, up to two orders of magnitude in some cases. Any detailed analysis of individual galaxies should thus be treated with caution, and quoted uncertainties in any derived results should reflect this.

The attenuation of the UV-derived SFRs, however, appears to be less effectively modelled. As shown by the dot-dashed lines in Figures 2(b) and 3(b) the attenuation implied at U-band by Equation 7 is insufficient to reproduce the observed $\mathrm{SFR_{UV}}$. The observations of local galaxies imply even greater levels of obscuration, and the degeneracy in observed UV luminosities with respect to intrinsic UV luminosity found by Adelberger & Steidel (2000) possibly suggest greater levels still. The trend seen by Adelberger & Steidel (2000) could be illustrated in Figures 2(b) and 3(b) by a horizontal line at $\mathrm{SFR_{UV}} \approx 1\,M_\odot\,\mathrm{yr}^{-1}$, for intrinsic SFRs $\gtrsim 1\,M_\odot\,\mathrm{yr}^{-1}$. This would intercept the solid line in these Figures at a value of intrinsic SFR $\approx 5\,M_\odot\,\mathrm{yr}^{-1}$, (less for the longer UV wavelength models) and the implied obscuration would be greater than given by Equation 7 (for $\lambda = 150\,\mathrm{nm}$) for objects with larger intrinsic SFRs. Again, knowledge of only the observed UV luminosity would be insufficient to establish the extent of the obscuration in the degenerate case.

To establish whether or not the trend seen in the local U-band measurements is consistent with the results of Adelberger & Steidel (2000), we have applied several robust regression algorithms (Isobe et al. 1990) to the data of Figures 2(b) and 3(b). We find positive, non-zero slopes in all cases, even when considering only data having values of intrinsic SFR $\gtrsim 1\,M_\odot\,\mathrm{yr}^{-1}$ (the "flattest" portion of these diagrams). Our best estimate of the slope, from the ordinary least squares bisector (Isobe et al. 1990), is 0.7 ± 0.07 (for logarithmic values of SFR), with a Pearson correlation coefficient of 0.5. This may be compared with an approximate slope of 0.68 (for $0.1 < \mathrm{SFR_{FIR}} < 10$) for the relation predicted by Equation 7 at 150 nm (*not* U-band). This result will be made use of in Section 6. While

it is possible that some incompleteness in the data has artificially skewed the slope to positive values, it is also possible that there is a real trend in the U-band data which is absent in the shorter wavelength (160 nm) data. This suggestion is not unreasonable, as the level of obscuration expected at U-band (365 nm) is less than at 160 nm for a given intrinsic luminosity, or SFR. It is also consistent with the non-degenerate trend seen in Figure 3 of Sullivan et al. (2001) based on 200 nm observations. If this is the case, then it is possible that a method similar to the one we analyse here may be useful for correcting UV observations at wavelengths between U-band and 160 nm. Indeed, it should be emphasised that the empirical trends presented by the UV data (both in Figures 2(b) and 3(b), as well as Figure 3 of Sullivan et al. 2001, and in Adelberger & Steidel 2000) are still evidence of a form of SFR-dependent obscuration, albeit one implying even greater levels of attenuation than predicted by Equation 7.

5. Corrections to global SFR density

We have so far considered the effects of a SFR-dependent obscuration on samples of galaxies taken from the local universe. Now, building on the conclusions of the previous Section, we consider how this might affect the evolution of the global SFR density, given the simplified assumption of no evolution in the properties or effects of dust. In light of the shortfall in the level of attenuation predicted by Equation 7 we will treat the magnitude of the predicted corrections to $\rho^*_{\rm UV}$ as lower limits to the required correction, and examine the resulting implications.

In applying the SFR-dependent reddening correction to samples at high redshifts, we need to assume that the locally-derived trend between obscuration and SFR is still valid. Obviously this may not be the case, particularly since our understanding of galaxy evolution implies that the metallicity of the inter-stellar medium increases with time. For example, Steidel et al. (1999) find a dearth of high-redshift galaxies with $E(B-V) \gtrsim 0.3$. Extremely red galaxies, a class of objects defined by $R-K>6$, may actually be a population of dusty star-forming galaxies at high redshifts (e.g. Cimatti et al. 1999; Andreani et al. 2000), however, so the extent of obscuration at high redshifts is still unclear (but see also the discussion of such objects in Adelberger & Steidel 2000). In the absence of more extensive evolutionary constraints, we begin with this simple assumption and anticipate that (1) evolutionary effects may be able to be incorporated as more data becomes available, and (2) remaining discrepancies will serve to direct attention to those wavelengths and redshifts deserving of further investigation.

5.1. Applying the correction

We present a compilation of uncorrected global SFR density (ρ^*) measurements in Figure 4. This emphasises the magnitude of the attenuation corrections required to reconcile the various estimates at different wavelengths. In addition to the UV surveys (Connolly et al. 1997; Treyer et al. 1998; Steidel et al. 1999; Sullivan et al. 2000) and Hα surveys (Gallego et al. 1995; Tresse & Maddox 1998; Yan et al. 1999; Hopkins et al. 2000), we also show results from FIR observations (Rowan-Robinson et al. 1997; Flores et al. 1999) and 1.4 GHz radio surveys (Haarsma et al. 2000; Serjeant et al. 2000; Condon 1989). All measurements have been converted to our assumed cosmology and SFR calibrations for consistency.

To correct existing UV and Hα estimates of ρ^* using the SFR-dependent reddening formulation described above requires a knowledge not just of ρ^* itself, but of the appropriate Hα or UV luminosity function, since the corrections to be applied are SFR (and hence luminosity) dependent. We have initially considered our derived relations, applying the corrections derived from Equations 5 and 7 for a number of published Hα and UV surveys, sampling a broad redshift range. The results are shown in Figure 5.

The local 1.4 GHz measurement from Serjeant et al. (2000) of $\rho^*_{1.4} = 0.031 \pm 0.007\, M_\odot {\rm yr}^{-1}{\rm Mpc}^{-3}$ (after converting to $H_0 = 75$ and using our assumed ${\rm SFR}_{\rm 1.4GHz}$ calibration), derived from a measurement of the local 1.4 GHz LF of Revised Shapley-Ames spiral galaxies, is consistent with the value of $\rho^*_{1.4} = 0.036\, M_\odot {\rm yr}^{-1}{\rm Mpc}^{-3}$ obtained by integrating the local 1.4 GHz LF for spiral galaxies from Condon (1989).

Also shown in Figure 5 are two models for the evolution of ρ^*. The solid line is derived from a fit to the evolving 1.4 GHz LF for star-forming galax-

ies, measured by Haarsma et al. (2000) and based on the local LF of Condon (1989), and is anchored at $z = 0$ by that point. The dashed line is a model for the FIR luminosity density derived by Gispert et al. (2000) from measurements of the cosmic far-infrared background. This model has been converted to SFR density using the SFR calibration of FIR luminosity given by Kennicutt (1998).

5.2. Discussion

The effectiveness of correcting estimates of ρ^* by assuming an SFR-dependent obscuration is discussed separately below for three broad redshift regimes.

5.2.1. $0 < z \lesssim 0.3$

For redshifts out to $z \approx 0.3$ applying the SFR-dependent correction to (1) the uncorrected UV LFs of Sullivan et al. (2000) and Treyer et al. (1998), and (2) the N[II] and aperture corrected (but not extinction corrected) Hα LF of Tresse & Maddox (1998) all give consistent results. The magnitude of the correction for $\rho^*_{\rm UV}$ in this redshift range is a factor of about 3. While this correction may need to be considered a lower limit the true value is probably not much greater than this, since both corrected $\rho^*_{\rm UV}$ estimates and the corrected $\rho^*_{\rm H\alpha}$ estimate are consistent with the trend in the radio-based ρ^* measurements spanning this redshift range (see also Section 6).

The one remaining discrepancy is a factor of $2-3$ difference between the 1.4 GHz and Hα based estimates of ρ^* at $z \approx 0$. The results of Gallego et al. (1995) are shown in Figure 5 with the reddening correction originally applied by those authors. Mobasher et al. (1999) have also derived a local Hα SFR density which is consistent with this measurement. The SFR-dependent formulation results in a correction similar to the ≈ 1 magnitude often assumed for this local population, and is unlikely to increase by more than a few tens of percent the value of Gallego et al. (1995). (At higher redshifts the evolving Hα LF provides greater numbers of higher luminosity systems, which results in larger corrections to $\rho^*_{\rm H\alpha}$.)

Serjeant et al. (2000) address this discrepancy by suggesting that a significant fraction of star formation occurs in the cores of giant molecular clouds, which would imply much greater obscuration than derived from a Balmer decrement reddening correction assuming a simple dust screen. Regardless of the mechanism, however, the obscuration must be such that it explains the observed trends of Figures 2 and 3. Hence, at least in the local universe, the correction cannot be much greater than that which we examine in this analysis. At higher redshifts, perhaps, the amount of attenuation could be greater, although the trend of Figure 2(a) is sufficient to explain the discrepancy in $\rho^*_{\rm H\alpha}$ at $z \approx 1$ (see Section 5.2.2).

An alternative explanation for this discrepancy questions the calibration of $\rm SFR_{1.4GHz}$. This is ultimately based on the calibration of non-thermal radio luminosity, L_N, to supernova rate, ν_{SN}, in our own galaxy (Condon 1992). If the escape of cosmic ray electrons from our galaxy is significant, lowering the observed L_N for a given SFR, then the derived calibration constant will be larger than had we seen all the radio emission. Hence, in external systems where we may see more, even most, of the radio emission produced by the star-formation, the derived SFR will be too great. Condon (1992) argues against this scenario, however, stating that significant variations in the ratio L_N/ν_{SN} would violate the observed radio-FIR correlation.

A third possibility is suggested by preliminary estimates of the local Hα luminosity density from the KPNO International Spectroscopic Survey (KISS, Gronwall et al. 1997, 1999; Salzer et al. 2000). This survey finds a local Hα luminosity density somewhat higher than that measured by Gallego et al. (1995).

5.2.2. $0.3 \lesssim z \lesssim 2.0$

Within this redshift regime there is a discrepancy between estimates of $\rho^*_{\rm FIR}$ from different analyses. For $0.3 \lesssim z \lesssim 1.0$, the FIR-based values of Rowan-Robinson et al. (1997) are comparable to the radio-based results of Haarsma et al. (2000), but those of Flores et al. (1999) lie a factor of $\approx 1.5-2$ lower (Figure 4). Possible sources for this discrepancy have been discussed by Flores et al. (1999), who emphasise that their analysis covers a much larger area than that of Rowan-Robinson et al. (1997), and uses different methods for fitting galaxy spectral energy distributions.

From $0.6 \lesssim z < 2.0$, the application of the

SFR-dependent reddening to Hα LFs (Yan et al. 1999; Hopkins et al. 2000) results in SFR densities which are consistent with the observational radio-derived values, and the FIR-derived values of Rowan-Robinson et al. (1997). This is highly encouraging, and suggests that the form of SFR-dependent reddening described by Equation 5 may be applicable as far out as $z \approx 2$. It also implies little evolution in the form and extent of obscuration, at least in a global, population-averaged sense. Obviously details for individual galaxies will vary significantly, as evidenced by the large scatter in Figures 2 and 3. The integration of the luminosity function to derive estimates of ρ^* has the effect of averaging over this scatter, minimising its effect. The resulting integral measure is thus more robust to the variations in individual galaxies, and reflects instead the general trend such as that modelled by Equation 5. A further observational estimate of $\rho^*_{\mathrm{H}\alpha}$ at $z \approx 0.9$ (Glazebrook et al. 1999, not shown in Figures 4-6) may also be consistent with these results, as they comment that their value is consistent with the "high" estimate of Rowan-Robinson et al. (1997) if they apply the Calzetti prescription for dust attenuation.

The same treatment with the UV LFs of Connolly et al. (1997) give a factor of ≈ 4 corrections to ρ^*_{UV}. The corrected ρ^*_{UV} still lies a factor of $\approx 1.5 - 2$ lower than ρ^*_{FIR}, $\rho^*_{1.4\mathrm{GHz}}$ or the corrected $\rho^*_{\mathrm{H}\alpha}$ (Figure 5). This is not unexpected, and is consistent with the interpretation of Equation 7 as providing lower limits for the corrected ρ^*_{UV}.

It is possible, on the other hand, that lower metallicities and obscurations at higher redshifts for galaxies of a given luminosity imply some evolution in the calibration of $\mathrm{SFR}_{\mathrm{UV}}$. Such an effect would be in the sense that a given *observed* UV luminosity at higher redshifts implies *lower* levels of SFR. This would give a calibration coefficient which decreases with redshift, reducing the observed ρ^*_{UV}, and the correction for any obscuration would also decrease with redshift. If this effect is large enough, it could exacerbate the discrepancy between ρ^*_{UV} and the 1.4 GHz and FIR estimates. This extreme scenario would be inconsistent with the results of the Hα corrections in this redshift regime, which suggest that any such evolution in the level of obscuration is probably small.

5.2.3. $z \gtrsim 2.0$

At the high redshift end, $z \approx 3 - 4$, the UV LFs of Steidel et al. (1999) have also been re-examined assuming an SFR-dependent reddening. Despite the large uncertainties associated with extrapolating Equation 7 to high redshifts, and the expectation that in its present form the correction is likely to be underestimated, it is encouraging to see that the results lie midway between the predictions of the two models shown. The corrected estimates using Equation 7 are bracketed by the predictions from the model evolving radio LF and the FIR background model. They are also consistent with the lower limit derived from sub-mm SCUBA observations of the Hubble Deep Field (Hughes et al. 1998), $\rho^* > 0.16\,M_{\odot}\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$ in our cosmology. The correction derived from Equation 7 approaches a factor of 10 at $z \approx 4$, and may *still* need to be considered a lower limit to the true correction given the results of Adelberger & Steidel (2000). The extremely large uncertainties associated with extrapolating the locally-derived SFR-dependent reddening models to such high redshifts, though, dictate the use of caution when interpreting these results. It is still interesting to note that if these corrections are indeed underestimates and the true values need to be higher, they would lie closer to the extrapolations from the 1.4 GHz luminosity functions estimated by Haarsma et al. (2000), almost an order of magnitude above the estimates from the FIR background.

6. An empirical investigation

The inadequacy of Equation 7 in fully explaining the observed levels of obscuration prompts two questions. The obvious one relates to the origin of the obscuration, and is discussed briefly below. The second is: "Independent of the mechanism producing the obscuration, is the local *empirical* relation between $\mathrm{SFR}_{\mathrm{UV}}$ and intrinsic SFR sufficient to explain the discrepancies in ρ^* at higher redshifts?" We examine this by applying the empirical relationship for local galaxies observed in Figures 2(b) and 3(b) to ρ^*_{UV} measurements at all redshifts.

For this simple analysis we treat the relationship between $\mathrm{SFR}_{\mathrm{UV}}$ and $\mathrm{SFR}_{\mathrm{FIR}}$ (or $\mathrm{SFR}_{1.4\mathrm{GHz}}$) described by the $0.15\,\mu$m attenuation (the solid

curve in these Figures) as a mathematically convenient description of this empirical relation. We also assume this relationship is valid at shorter wavelengths (where the attenuation may be still greater, given the results of Adelberger & Steidel 2000), but particularly at $0.28\,\mu$m, where the measurements from Connolly et al. (1997) were made. Applying the SFR-dependent correction to all the $\rho^*_{\rm UV}$ points based on this empirical result gives the diagram shown in Figure 6. Good agreement is now seen between all UV, Hα and radio-derived values for ρ^*. The effectiveness of this application is dominated by the effective correction to the data of Connolly et al. (1997), since the corrections at low-redshift are not modified greatly (due to the LF being dominated by lower-luminosity sources). The primary conclusion here is that the empirical relation between local U-band estimates of $\rm SFR_{UV}$ and intrinsic SFR is sufficient to account for obscuration in 280 nm observations at $z \approx 1.5$.

Two possible scenarios to explain the shortcomings of Equation 7 are discussed in this light. First, dust in star forming galaxies may be characterised by a reddening curve even greyer than that of Calzetti et al. (2000). The situation may be explained if the attenuation at wavelengths between $0.15 < \lambda \lesssim 0.4\,\mu$m is comparable to that observed locally in U-band. One model producing this effect may be a heavily dust-enshrouded starburst, optically thick below $0.4\,\mu$m, but having "holes" which allow some portion of UV light to escape unattenuated. This would result in a uniform "blocking" of all emission below the optically thick cutoff, and produce the required constant attenuation as a function of (UV) wavelength. The effective reddening curve for this scenario may, however, not be consistent with the results of the FIR dust luminosity analysis presented in Calzetti et al. (2000). Alternatively, the dust attenuation remains as given by Calzetti et al. (2000), but there is some additional process which needs to be invoked to explain the shortfall in the U-band derived SFRs seen in Figures 2(b) and 3(b). This may be the case, for example, if the relative contribution of the old stellar population to the U-band luminosity is greater at low SFR. (Luminosities at shorter UV wavelengths would have less "contamination" from the old stars, so would be affected less or not at all in this scenario.) This would imply that the U-band derived SFRs in low-SFR systems are *over*-estimated, and need to be revised downward. Then, combined with a suitable revision of the U-band/SFR calibration, this would account for the discrepancies. There are still problems with this suggestion as well, since low-SFR systems also tend to be low-luminosity systems (e.g. Cram et al. 1998, their Figure 3), and this implies the *relative* contribution from the old stellar population may not change much with SFR.

In addition, whatever mechanism is invoked needs to be able to reproduce the degenerate relationship between observed UV luminosity and obscuration at shorter wavelengths found by Adelberger & Steidel (2000). More investigation of the result described here is obviously still required. Although the application of the locally observed empirical $\rm SFR_{UV}$ to $\rm SFR_{FIR}$ relation to shorter wavelengths and higher redshifts may account for the $\rho^*_{\rm UV}$ discrepancies it does not explain their physical origin. It does emphasise that the trend observed locally in U-band is consistent with the discrepancies at much higher redshifts and at shorter wavelengths. This is consistent with the result for the Hα correction suggesting little net evolution, if any, in the level of obscuration at least out to $z \approx 2$.

7. Conclusions

We have modelled an SFR-dependent attenuation by dust, characterised by the Calzetti reddening curve. Corrections derived from this model have been applied to a large sample of local galaxies, spanning a wide range in intrinsic SFR, to examine the effects on local Hα- and UV-derived SFR estimates. Subsequently, measurements of ρ^* for a broad range of redshift have also been corrected using this model. It is clear from the observational data investigated here, as well as the smaller samples of Wang & Heckman (1996) and Calzetti et al. (1995), that some form of SFR-dependent extinction is implied. The investigated prescription appears sufficient to explain the general trend between $\rm SFR_{H\alpha}$ and $\rm SFR_{1.4GHz}$ or $\rm SFR_{FIR}$. It also accounts for the discrepancies between estimates of $\rho^*_{\rm H\alpha}$ and $\rho^*_{\rm 1.4GHz}$ or $\rho^*_{\rm FIR}$ out to $z \approx 2$, with the exclusion of the local $\rho^*_{\rm H\alpha}$ estimate of Gallego et al. (1995). This is strongly suggestive of little or no evolution in the extent

or form of the obscuration at rest-frame Hα wavelengths. As a result, this may serve as a useful tool in making corrections for obscuration in estimates of $\mathrm{SFR_{H\alpha}}$ or $\rho^*_{\mathrm{H}\alpha}$ in the absence of more direct methods (such as for the NICMOS grism surveys of Yan et al. (1999) and Hopkins et al. (2000), and the recent SOFI/ISAAC results of Moorwood et al. (2000), which lack Balmer decrement information).

The examined prescription for correcting UV-based estimates of SFR and ρ^* was less effective. Although the predicted corrections reduce the level of observed discrepancy with obscuration-free estimators, they do not fully account for the observed levels of attenuation in local U-band estimates of $\mathrm{SFR_{UV}}$. There may also be concerns that a degenerate relation (at shorter wavelengths) would prevent application of the iterative method used. The use of this method to estimate lower limits for the corrections to ρ^*_{UV} is more encouraging, though, particularly for $z \lesssim 0.3$ where the magnitude of the required correction is unlikely to increase by much. The situation becomes more complex at higher redshifts, and here evolutionary effects, as well as a more complete understanding of the obscuration in galaxies at UV-wavelengths, may need to be incorporated.

The empirical relationship observed at U-band for local galaxies between $\mathrm{SFR_{UV}}$ and $\mathrm{SFR_{FIR}}$ or $\mathrm{SFR_{1.4GHz}}$ was also examined. It was used to correct high-redshift estimates of ρ^*_{UV}, resulting in values consistent with $\rho^*_{\mathrm{1.4GHz}}$ and ρ^*_{FIR} for UV wavelengths longer than 160 nm. This may support the result from the Hα analysis, suggesting minimal evolution in the extent of dust obscuration. The mechanisms producing the obscuration are still in question, and prompt further investigation of dust models and the characteristics of dust on UV-wavelength radiation.

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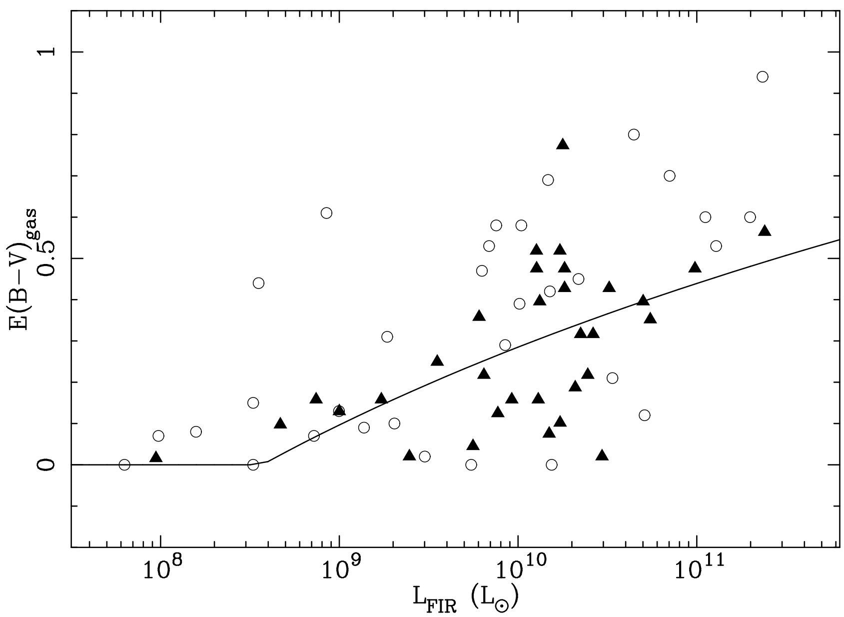

Fig. 1.— The colour excess $E(B-V)$ as a function of FIR luminosity. Solid triangles: data from Wang & Heckman (1996, their Figure 10 with Balmer decrement converted to colour excess); Open circles: starburst and blue compact galaxies from Calzetti et al. (1995). The solid line shows the relation between colour excess and FIR luminosity derived from combining Equations 1 and 2.

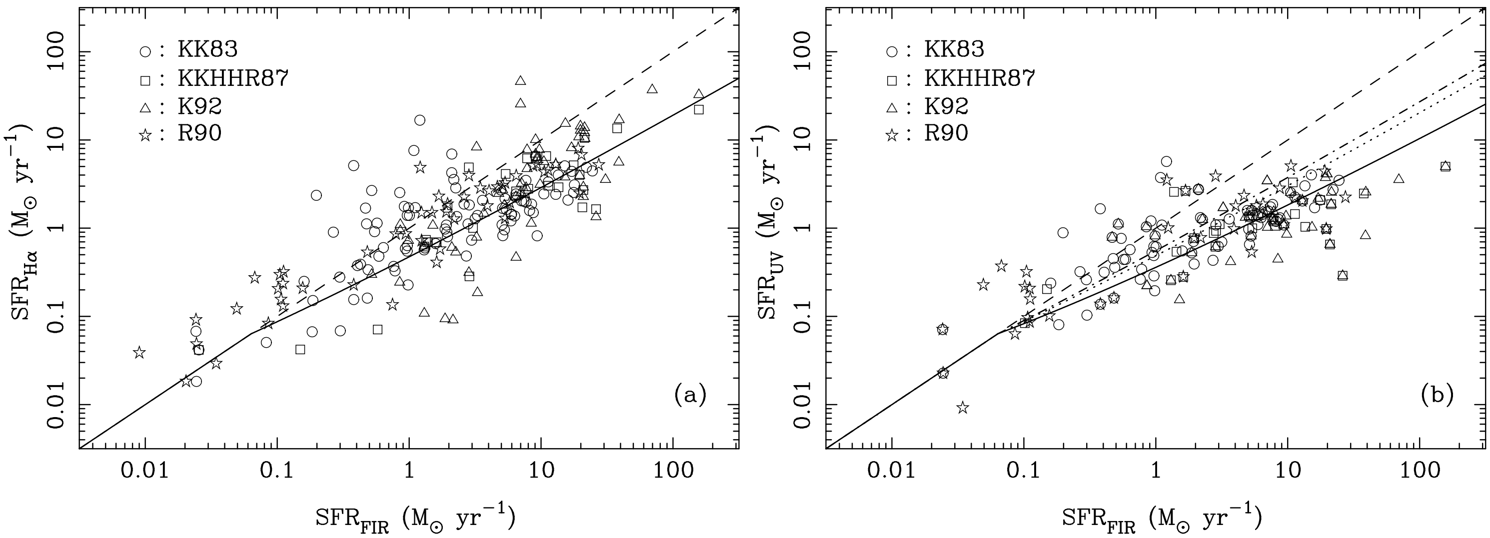

Fig. 2.— (a) $SFR_{H\alpha}$, and (b) SFR_{UV}, both uncorrected for extinction, compared to SFR_{FIR}. The SFR_{FIR} values here come from measurements of the $60\,\mu$m luminosity, and the SFR_{UV} values come from U-band (365 nm) measurements. Both of these are converted to SFR using the calibrations of Cram et al. (1998), after adjusting by a factor of 5.5 to account for stellar masses $< 5\,M_\odot$. Both calibrations are consistent with those of Kennicutt (1998). The solid line shows the SFR-dependent attenuation, calculated using the prescription described in the text, for (a) Hα and (b) UV($\lambda = 0.15\,\mu$m). The dashed line shows a one-to-one relationship. The dot-dashed and dotted lines in (b) are for the attenuations valid at $\lambda = 0.365\,\mu$m (U-band) and $0.28\,\mu$m respectively. It can easily be seen that the U-band attenuation in this formulation is not sufficient to reproduce the observed trend. The different symbols mark different sources for the data (see also Cram et al. 1998): KK83: Kennicutt & Kent (1983); KKHHR87: Kennicutt et al. (1987); K92: Kennicutt (1992); R90: Romanishin (1990).

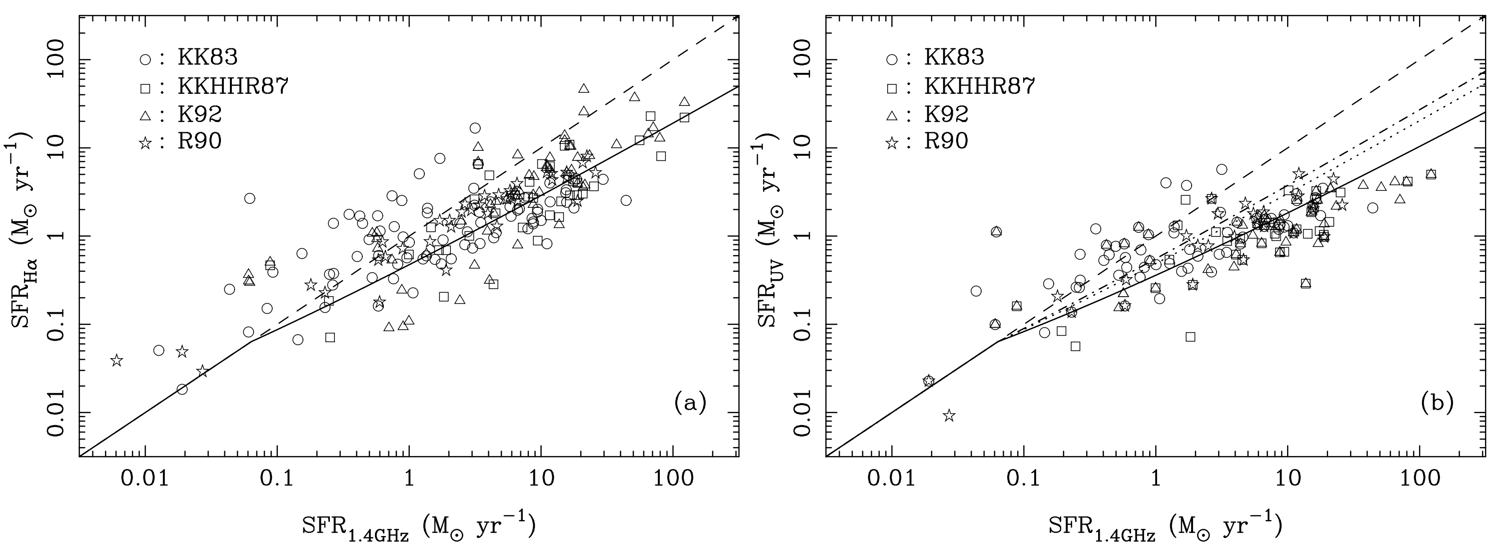

Fig. 3.— As above, but relative to 1.4 GHz derived SFRs instead of FIR, emphasising the importance of 1.4 GHz based estimates of SFR and hence ρ^*.

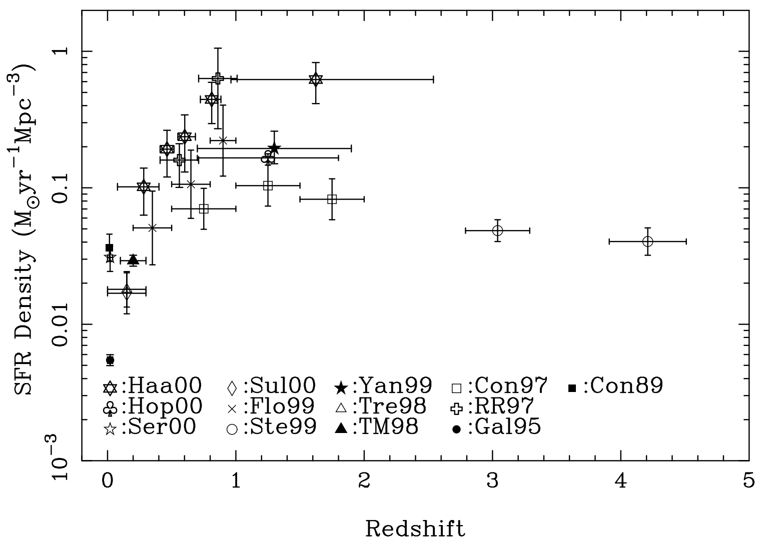

Fig. 4.— SFR density (ρ^*) as a function of redshift. This diagram is a compilation of SFR densities derived from various existing sources, with no reddening corrections applied to any data. The reddening-corrected measurement of Gallego et al. (1995) has been artificially "reddened" by 1 magnitude for comparison with other uncorrected data in this diagram (solid circle). References in diagram are as follows, along with the origin of the ρ^* estimate: Haa00: Haarsma et al. (2000) (1.4 GHz); Hop00: Hopkins et al. (2000) (Hα); Ser00: Serjeant et al. (2000) (1.4 GHz); Sul00: Sullivan et al. (2000) (UV); Flo99: Flores et al. (1999) (FIR); Ste99: Steidel et al. (1999) (UV); Yan99: Yan et al. (1999) (Hα); Tre98: Treyer et al. (1998) (UV); TM98: Tresse & Maddox (1998) (Hα); Con97: Connolly et al. (1997) (UV); RR97: Rowan-Robinson et al. (1997) (FIR); Gal95: Gallego et al. (1995) (Hα); Con89: Condon (1989) (1.4 GHz).

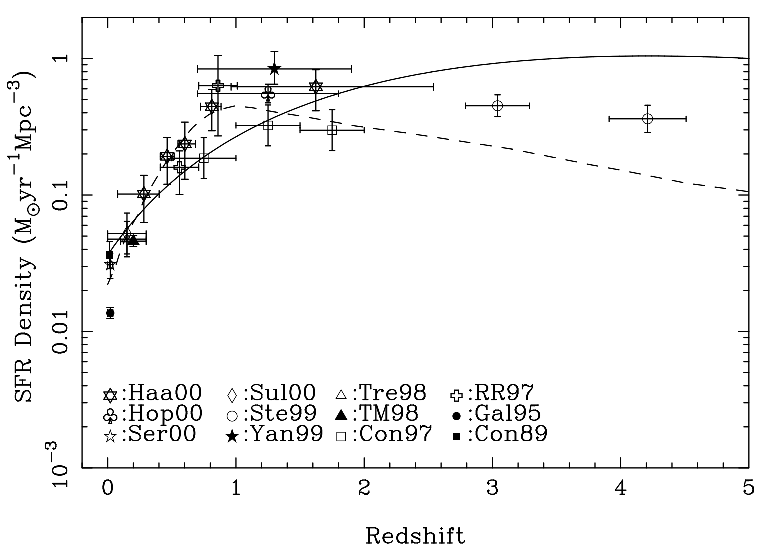

Fig. 5.— SFR density (ρ^*) as a function of redshift. This diagram shows the same data as in Figure 4 with the Hα and UV based measurements corrected using the SFR-dependent reddening prescription. The FIR measurements of Flores et al. (1999) have been omitted in this diagram for clarity. The solid curve comes from the evolving 1.4 GHz radio luminosity function for star-forming galaxies derived by Haarsma et al. (2000). The dashed curve is a model derived from the cosmic far-infrared background by Gispert et al. (2000). References are as for Figure 4.

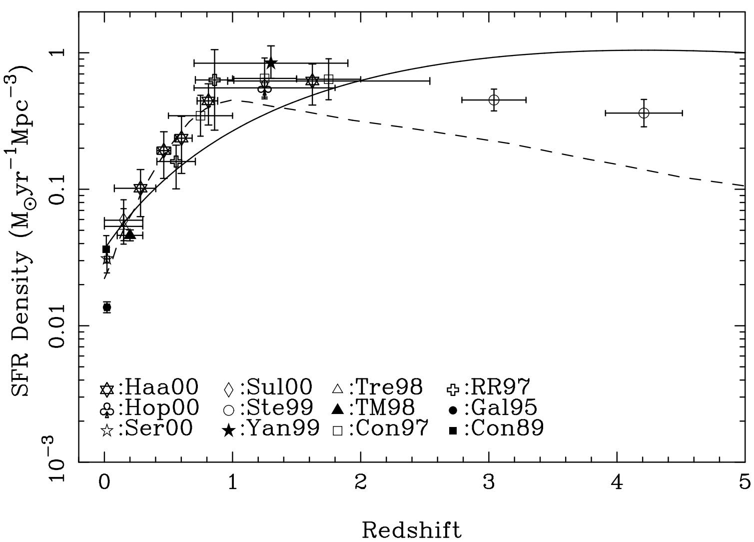

Fig. 6.— SFR density (ρ^*) as a function of redshift. This diagram is identical to Figure 5 except that the $\rho^*_{\rm UV}$ values have all been corrected using the SFR-dependent reddening with $k(\lambda) = k(0.15\,\mu{\rm m})$, to examine the effects of applying the locally observed empirical relationship between ${\rm SFR_{UV}}$ and ${\rm SFR_{FIR}}$ to all redshifts.